Multidimensional Digital Signal Processing, Devices for Information Processing, and Electromagnetic Analysis and Measurement

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This final report covers research carried out under Contract DAAH-04-96-1-0161 for the period June 1, 1996 through September 30, 1999. Research activities are concentrated in the following areas: multidimensional digital signal processing, optical storage and information processing, and electromagnetic measurements. Individual work units involve research in multidimen-sional digital signal processing and modeling, stereo and multiview image processing, nonlinear systems for image and video signal processing, linear multidimensional multiresolution processing, optical devices for information processing, semiconductor quantum wave devices, electromagnetic analysis and measurements in the time and frequency domains, and far-field, compact and near-field antenna measurement facility compensation.

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CONTENTS

1	**OVERVIEW**	
1.1	Progress in Multidimensional Digital Signal Processing	1
1.2	Progress in Optical Devices for Information Processing	4
1.3	Progress in Electromagnetic Analysis and Measurement	5
2	**Work Units and Principal Investigators**	6
3	**Doctoral Degrees Awarded**	7
4	**Publications**	8

1 OVERVIEW

This is the Final Report on research carried out under Contract DAAH-04-96-1-0161 for the period June 1, 1996 through September 30, 1999. The research was part of the Joint Services Electronics Program (JSEP) and was administered by the U.S. Army Research Office. The research in this program was concentrated in the following broad areas of electronics:

- Multidimensional Digital Signal Processing
- Optical Devices for Information Processing
- Electromagnetic Analysis and Measurement

The details of research progress in this program have been given in three annual reports. This final report gives in Sections 1.1 – 1.3, a brief review of some of the significant results during the term of the contract. The principal investigators of the individual work units are listed in Section 2; the doctoral degrees awarded on research during the contract period are listed in Section 3; and the publications during the reporting period are listed in Section 4.

1.1 Progress in Multidimensional Digital Signal Processing

Research in multidimensional signal processing was carried out in four work units. The work in this area was concerned with video coding and interpolation, the use of hidden Markov models in multimedia communication and in face recognition, stereo image compression, motion and disparity estimation, implementation of nonlinear image operations using partial differential equations, wavelet transform theory and applications, 3-D subband coding, adaptive and directional filterbanks, target tracking in video sequences, and multidimensional filter design algorithms for complex frequency responses. Several research highlights are described briefly below.

- **Rate-Quality Based Video Coding**

A doctoral thesis by F.-H. Lin produced new results on the trade-off between perceived quality and bit-rate in video coding. The work presents a new objective measure of quality that correlates well with perceived video quality. Linear regression was used to find sets of measured features that have a high correlation with perceptual ratings of distorted video sequences. Then a new measure was designed by using a nonlinear regression implemented with a neural network to select combinations of the best features. The result was an objective measure with more than 96% correlation with the subjective data base. This measure was used to design MPEG video encoders that allow very flexible tradeoff between quality and bit-rate while out-performing the MPEG Standard reference encoder by about half a quality point (on a 5-point scale).

- **New Approach to Sensor Fusion**

Doctoral work by R. Rao was concerned with using hidden Markov models (HMMs) to perform pattern recognition on data from two different modalities. It looks specifically at the information in the video and audio tracks of video recordings of people talking, but the results are potentially applicable to many other types of sensor fusion applications. Two very specific questions that the research seeks to answer are: can the performance of speech recognizers be improved when the video signal is used, particularly in high acoustic noise environments? and can a realistic synthetic video signal be generated from just the audio signal? Results of the research suggest that our approach can yield significant improvement. Our approach uses an audio-visual HMM to characterize the audio-visual recording; this is trained using audio-visual data. This HMM is used directly for the recognition problem and is projected into the audio subspace for the synthetic video problem. We are also preparing to transfer this approach to the problem of target classification in SAR imagery, where target and shadow returns form the two distinct signal classes.

- **Hidden Markov Models in Face Recognition**

Research conducted in face detection and face recognition resulted in the completion of a Ph.D. thesis by Ara Nefian in August 1999. The use of hidden Markov models (HMM) for faces is motivated by their partial invariance to variations in scaling and by the structure of the faces. The most significant facial features of a frontal face include the hair, forehead, eyes, nose, and mouth. These features occur in a natural order, from top to bottom, even if the images undergo small rotations in the image plane, and/or rotations in the plane perpendicular to the image plane. Therefore, the image of a face may be modeled using a one-dimensional HMM by assigning each of these regions to a state. The observation vectors are obtained from the DCT or KLT coefficients. A one-dimensional HMM may be generalized, to give it the appearance of a two-dimensional structure, by allowing each state in a one-dimensional HMM to be an HMM. In this way, the HMM consists of a set of super states, along with a set of embedded states. Therefore, this is referred to as an embedded HMM. The super states may then be used to model two-dimensional data along one direction, with the embedded HMM modeling the data along the other direction. Both the standard HMM and the embedded HMM were tested for face recognition and detection. Compared to other methods, the proposed system offers a more flexible framework for face recognition and detection and can be used more efficiently in scale-invariant systems.

- **Partial Differential Equations and Nonlinear Image Processing**

The Ph.D. thesis of M. Akmal Butt concerned the optimization of the discrete distance transforms and the presentation of new methodologies for the efficient implementation of PDE-based algorithms. New optimal discrete distance transforms under various optimization criteria were found and new methods developed for their faster implementation. The new algorithms were applied to the problems of multiscale image analysis, shape recovery, gridless halftoning, ray tracing, and image segmentation.

- **Defeating Countermeasures Using Wavelets**

In the ideal case with high target contrast and a benign background, simple algorithms for target tracking can work well. However, in practical situations, simple algorithms often fail to yield robust performance. Moreover, when aircraft are equipped with countermeasures, such as flares, the problem is further exacerbated. We have been investigating a wavelet transform formulation that promises to help in addressing this difficult tracking problem. The transform effectively maps the input signal space to a physically meaningful parameter space, where motion parameters (i.e. position, velocity, and size) are explicit in the representation. A set of local energy densities is defined by partially integrating the wavelet transform energy on subsets of the parameter space. These energy densities are then used to extract motion parameters. The algorithm consists basically of a frame-by-frame sequential optimization of motion parameters by maximizing the associated energy densities. Because the wavelet is a space-time filter, it tends to integrate the noise, resulting in noise suppression. The effectiveness of the algorithm against aircraft equipped with flare decoys has been demonstrated with experiments on real data.

- **Complex Multidimensional Filter Design**

The Remez exchange algorithm for FIR linear-phase filter design has been extended to the case where the desired filter response is specified in both magnitude and phase. This new theoretical result makes possible the rapid design of optimal filters whose complex frequency response characteristics are fully specified. One application is in minimum-delay filter design, where nearly linear phase filters are needed to avoid inter-symbol interference. Another significant application is in the phase-only processing needed in a wave-propagation filter such as migration for seismic or SAR processing. The new filter design algorithm has guaranteed convergence to the optimum under a mild set of conditions. Our work has given proofs of the conditions where this method will converge, and we developed a two-phase algorithm that uses the quickly converging Remez solution as the starting point of a second iteration that will find the true optimum in all cases. This second iteration is only needed when the theoretical conditions on the number of alternations is not met and the Remez exchange algorithm has converged to a sub-optimum filter. In a related line of research, we have recently generalized these complex-valued filters to the multidimensional case so that 2-D and 3-D migration filters can be designed as transformations of 2-D phase-only designs. This transformation strategy has also been used to design filter families that embed several low dimensional filters in a higher dimensional filter which can then be projected onto a lower dimension to extract one member of the family. For example, a set of 1-D migration filters with varying cutoff frequencies will define the ideal magnitude (and phase) characteristic of a 2-D fan filter. If the fan filter is designed by a transformation method, the various members of the filter family can be generated from one base filter.

- **Theory of Adaptive Filterbanks**

Significant progress has been made on the theory and implementation of adaptive filterbanks. Such filterbanks have been demonstrated to improve performance in subband image coding applications where the adaptive filters help to ease blocking effects and improve robustness to channel errors. Adaptive filterbanks have also been applied in the

problem of denoising of SAR images and found to outperform other denoising methods based on wavelet transforms.

1.2 Progress in Optical Devices for Information Processing

Research in optical devices was carried out in two work units that were focused on optical devices for information processing and semiconductor quantum wave devices. The work in this area produced significant results in the following areas: diffraction gratings, lenses, and couplers; multilayer optical waveguides; optical interconnects for massively parallel processors; quantum wave heterostructures; quantum wave interference filters; ballistic electron emission spectroscopy; silicon-based quantum wave devices; scanning tunneling microscopy; quasi-bound-state analysis techniques; and infrared lasers. Several research highlights are described briefly below.

- **Volume Diffractive Coupler**

A new device for diffracting light in a waveguide or substrate has been invented. This device and its method of fabrication will provide high diffraction efficiency, low cost to fabricate and install, and will reduce the need for separate optical components such as graded index lenses. A typical application for the device wold be to operate on an astigmatic three-dimensionally diverging beam from a semiconductor laser and diffract it into a guided wave in a slab waveguide in an integrated circuit.

- **Silicon-Based Quantum Semiconductor Devices**

A new design methodology has been developed for silicon-based semiconductor devices for use as optical emitters, detectors, modulators and switches. The devices are based on quantum wave Fabry-Perot filters implemented by a number of thin semiconductor layers. The research has developed a design process for determining the complex set of layers needed to create devices with differing functionality. Once the layers are designed, they can be grown by molecular beam epitaxy or metalorganic chemical vapor deposition. A primary advantage of these devices is that their fabrication is compatible with conventional silicon microelectronics technology, which allows them to be incorporated directly into silicon integrated circuits.

- **Electron-Wave Interference Effects in a $Ga_{1-x}Al_xAs$ Single-Barrier Structure Measured by BEE Spectroscopy**

Ballistic electron emission spectroscopy (BEES) was performed on a $GaAs/Ga_{0.8}Al_{0.2}As/GaAs$ single-barrier structure at 77 and 7 K. The single-interface model widely used for such structures was found to be inadequate in describing the BEES second-derivative spectrum. A more complete model that incorporates electron-wave interference effects was shown to describe the data accurately and consistently over many spatial locations and samples. This model reproduces all measured features in the BEES second-derivative spectrum resulting from electron-wave interference. At 77 K (7K), the conduction band offset for $x = 0.2$ is determined to be 145 meV or $Q_c = 0.58$ (150 meV or $Q_c = 0.60$) in agreement with accepted values.

- **Finite Substrate Thickness Diffractive Lenses**

A novel approach to the analysis of finite-substrate-thickness cylindrical lenses has been developed. This approach is based on the boundary element method (BEM), and allows the use of both exact and approximate Green's functions. The method allows the analysis of lenses with thicknesses of thousands of wavelengths for both TE and TM polarizations, and it can be used to study multiple resonance effects. The method has been used to solve problems that previously could not be analyzed with the BEM method.

- **Quasibound States in Arbitrary-Geometry Semiconductor Quantum Heterostructures**

A unified set of four numerical methods has been developed for determining the quasibound-state eigenergies and their lifetimes in quantum heterostructures having arbitrary potential profiles. The methods are applicable to devices of arbitrary geometries and potential profiles and are highly efficient and accurate.

1.3 Progress in Electromagnetic Analysis and Measurement

Research in EM analysis and measurement was carried out in two work units that were focused on time and frequency analysis techniques and on antenna range measurements. Significant research results were obtained in the following areas: finite-difference time-domain numerical techniques; pulse excited antennas; ground-penetrating radars; insulated linear antennas; and compensation techniques for spherical antenna ranges. Some highlights of this research are described briefly below.

- **Ground-Penetrating Radars for Mine Detection**

During this period, a major portion of the research on this work unit was concerned with the important problem of the detection of buried land mines. The first fully three-dimensional electromagnetic simulation of an actual detection system (the separated-aperture sensor) was performed. The simulation contained all of the details of the antennas (two dipoles with the reflectors an matching networks), the lossy soil, and the buried mine. The finite-difference time-domain (FDTD) numerical method was used for the simulation, and the computations were performed on computers at the University of Minnesota High-Performance Computing Research Center. The theoretical results were in good agreement with measurement. This research showed that such simulations can replace costly experimental measurements in the early stages of the design of such detectors.

- **Pulse Excited Antennas**

A study of methods to improve the performance of pulse excited antennas used in ground penetrating radars, such as those used for land mine detection has produced significant progress. Internal reflections within these antennas and multiple reflections between the antennas and the surface of the ground produce clutter than can obscure the return from the buried target (mine). A comprehensive study of the vee antenna showed that with the proper resistive loading this antenna can significantly reduce the clutter. The theoretical predictions were in good agreement with measurements. This study also showed

quantitatively the difficulty associated with identifying a given return as being from a mine and not from another buried object such as a rock.

- **Range Compensation in Spherical Far-Field and Compact Ranges**

Work has been completed on the plane wave, pattern subtraction, range compensation algorithm and a corresponding algorithm for modeling an antenna measurement range field using a small, selectable number of plane waves. The plane wave model of the range consists of a plane wave incident from the direction of the range antenna plus a small number of plane waves representing multipath reflections and equipment leakages. The range compensation algorithm removes errors introduced into an antenna pattern measurement by deviations of the range field from an ideal plane wave by estimating the response of the antenna to each of the plane waves in the model that represent the multipath reflections and equipment leakages and subtracting these errors from the measured pattern. Measurements have been performed that demonstrate the performance of the range compensation and plane wave modeling algorithms using an actual anechoic chamber.

2 Work Units and Principal Investigators

Work Unit One: Multidimensional Digital Signal Processing and Modeling
Dr. Russell M. Mersereau

Work Unit Two: Stereo and Multiview Image Processing
Dr. Ronald W. Schafer and Dr. Monson H. Hayes

Work Unit Three: Nonlinear Systems for Image and Video Signal Processing
Dr. Ronald W. Schafer

Work Unit Four: Linear Multidimensional Multiresolution Processing
Dr. James H. McClellan and Dr. Mark J. T. Smith

Work Unit Five: Optical Devices for Information Processing
Dr. Thomas K. Gaylord
Dr. Elias N. Glytsis

Work Unit Six: Semiconductor Quantum Wave Devices
Dr. Thomas K. Gaylord
Dr. Elias N. Glytsis

Work Unit Seven: Electromagnetic Analysis and Measurements in the Time and Frequency Domains
Dr. Glenn S. Smith

Work Unit Eight: Far-Field, Compact and Near-Field Antenna Measurement Facility Compensation
Dr. Edward B. Joy

3 Doctoral Degrees Awarded

F.-H. Lin – December 1996
Thesis: *Rate-Quality Based Video Coding*

S. Bayrakeri – May 1997
Thesis: *Scalable Video Coding using Spatio-Temporal Interpolation*

R. Rao – May 1998
Thesis: *Audio Visual Interaction in Multimedia*

H. Aydinoglu, – June 1997
Thesis: *Stereo Image Compression*

D. L. Brundrett – June 1997
Thesis: *Analysis, Design, and Applications of Subwavelength Gratings*

T. P. Montoya – March 1998
Thesis: *Vee Dipole Antennas for use in Short-Pulse Ground-Penetrating Radars*

A. Saidi – March 1998
Thesis: *Root Contours of Low-Order Two-Dimensional System Functions*

Q. H. Pham – June 1998
Thesis: *Hierarchical Processing Algorithms for Object Recognition*

D. Leatherwood – July 1998
Thesis: *Plane Wave, Pattern Subtraction, Range Compensation for Spherical Surface Antenna Pattern Measurements*

M. A. Butt – August 1998
Thesis: *Continuous and Discrete Approaches to Morphological Image Analysis with Applications: PDEs, Curve Evolution, and Distance Transforms*

D. K. Guthrie – December 1998
Thesis: *Analysis of Quantum Semiconductor Heterostructures by Ballistic Electron Emission Spectrocsopy*

R. Rau – December 1998
Thesis: *Postprocessing Tools for Ultra-wideband SAR Images*

A. Nefian – August 1999
Thesis: *A Hidden Markov Model-Based Approach for Face Detection and Recognition*

J. L. Arrowood – March 1999
Thesis: *Theory and Application of Adaptive Filter Banks*

4 Publications

MULTIDIMENSIONAL DIGITAL SIGNAL PROCESSING:

Work Unit One:

1. F.-H. Lin, *Rate-Quality Based Video Coding*, Ph.D. Thesis, Georgia Institute of Technology, Dec. 1996.
2. S. D. Bayrakeri and R. M. Mersereau, "An Effective Spatio-Temporal Interpolation Algorithm for Video Pyramid Coding," *SPIE Conf. Digital Video Compression*, vol. 2668, pp. 430-440, 1996.
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5. S. Bayrakeri and R. M. Mersereau, "MPEG-2 nonlinear temporally scalable coding and hybrid quantization,"" *Proceedings of the 1997 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 2629-2632.
6. F.-H. Lin, W. Gass, and R. M. Mersereau, "Video perceptual distortion measure: two-dimensional versus three-dimensional approaches," *Proc. 1997 IEEE Int. Conf. Image Processing*, vol. 3, pp. 460-463.
7. F.-H. Lin, W. Gass, and R. M. Mersereau, "Vision model based video perceptual distortion measure for video processing and applications," *Proc. 1997 IEEE Int. Conf. Acoustics, Speech, and Signal Processing*, pp. 3133-3138.
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9. R. R. Rao, *Audio Visual Interaction in Multimedia*, Ph.D. Thesis, Georgia Institute of Technology, School of Electrical and Computer Engineering, May 1998.
10. Tshuan Chen and Ram R. Rao, "Audio-visual Integration in Multimodal Communication," *Proc. IEEE*, vol. 86, no. 5, pp. 837-852, May 1998.
11. R. Rao, T. Chen, and R. Mersereau, "Audio-to-Visual Conversion for Multimedia Communication," *IEEE Transactions on Industrial Electronics*, vol. 45, no. 1, February 1998.

Work Unit Two:

1. H. Aydinoglu and M. H. Hayes, "Image Coding with Polynomial Transforms," *30th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, 1996.
2. H. Aydinoglu and M. H. Hayes, "Source Coding of Stereo Image Pairs," *4th Bayona Workshop on Intelligent Methods in Signal Processing and Communication*, Bayona, Spain, June 1996.
3. H. Aydinoglu, *Stereo Image Compression*, Ph.D. Thesis, Georgia Institute of Technology, June 1997.
4. H. Aydinoglu and M. Hayes, "Source Coding of Stereo Pairs," *Intelligent Methods in Signal Processing and Communications*, D. Docampo et. al., Ed., Birkhauser, Boston, pp. 281-299.
5. Qin Jiang and Monson H. Hayes III, "Stereo Sequency Coding," *SPIE, VCIP 1998.*

Work Unit Three:

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2. D. A. Florencio, Robert Armitano, and R. W. Schafer, "Motion Transforms for Video Coding," *Proc. 1996 Int. Conf. on Image Processing*, vol. 2, pp. 493-496, September 1996.
3. J. Crespo and R. W. Schafer, "Locality and Adjacency Stability Constraints for Morphological Connected Operators," *Journal of Mathematical Imaging and Vision*, pp. 85-102, 1997 Kluwer Academic Publishers, the Netherlands.
4. P. Maragos and M. A. Butt, "Advances in Differential Morphology: Image Segmentation via Eikonal PDE & Curve Evolution and Reconstruction via Constrained Dilation Flow,""in *Mathematical Morphology and Its Application to Image and Signal Processing*, H. Heijmans and J. Roerdink, Eds., Kluwer Academic Publishers, pp. 167-174, Boston, 1998.
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8. P. Maragos, M. A. Butt, and L. F. C. Pessoa, "Two Frontiers in Morphological Image Analysis: Differential Evolution Models and Hybrid Morphological/Linear Neural Networks," (invited talk), *Proceedings of International Symposium on Computer Graphics, Image Processing, and Vision* (SIBGRAPI-98), Rio de Janiero, Brazil, pp. 10-17, (IEEE Comp. Soc. Press), October 1998.

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DEVICES FOR INFORMATION PROCESSING:

Work Unit Five:

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